

Isospin Symmetry Breaking in Nuclei — ONS Anomaly —

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Abstract. We study the binding energy differences of the valence proton and neutron of the mirror nuclei, $^{15}\text{O} - ^{15}\text{N}$, $^{17}\text{F} - ^{17}\text{O}$, $^{39}\text{Ca} - ^{39}\text{K}$ and $^{41}\text{Sc} - ^{41}\text{Ca}$, using the quark-meson coupling model. The calculation involves nuclear structure and shell effects explicitly. It is shown that binding energy differences of a few hundred keV arise from the strong interaction, even after subtracting all electromagnetic corrections. The origin of these differences may be ascribed to the charge symmetry breaking effects set in the strong interaction through the u and d current quark mass difference. In this report, we first review the quark-meson coupling model. In particular, we discuss about the nucleon mass in nuclear medium. Then, we present details of the charge symmetry breaking in finite nuclei, especially the Okamoto-Nolen-Schiffer anomaly.

INTRODUCTION

The discrepancy between the calculated binding energy differences of mirror nuclei and those measured is a long-standing problem in nuclear physics. It is known as the Okamoto-Nolen-Schiffer (ONS) anomaly [1,2]. Although it was first thought that electromagnetic effects could almost account for the observed binding energy differences, it is now believed that the ONS anomaly has its origin in charge symmetry breaking (CSB) in the strong interaction [3]. In addition to calculations based on charge symmetry violating meson exchange potentials [3–5], a number of quark-based calculations have been performed [6,7] in an attempt to resolve this anomaly. In such calculations, CSB enters through the up (u) and down (d) current quark mass difference in QCD. Despite these efforts, the difficulty of producing a realistic description of nuclear structure on the basis of explicit quark degrees of freedom has hindered the direct calculation of the binding energy differences.

In this study we report the results for the binding energy differences of the valence (excess) proton and neutron of the mirror nuclei, $^{15}\text{O} - ^{15}\text{N}$, $^{17}\text{F} - ^{17}\text{O}$, $^{39}\text{Ca} - ^{39}\text{K}$ and $^{41}\text{Sc} - ^{41}\text{Ca}$, calculated using a quark-based model involving explicit nuclear structure and shell effects, namely the quark-meson

coupling (QMC) model [8]. This model has been successfully applied not only to traditional nuclear problems [8] but also to other new areas as well [9]. Although some exploratory QMC results on the ONS anomaly have already been reported [7], an early version of the model was used there, and it was applied to finite nuclei only through local density approximation, rather than a consistent shell model calculation.

THE QUARK-MESON COUPLING MODEL

In this section, we introduce the QMC model, and then report the medium modification of the nucleon properties in finite nuclei [8].

Effect of Nucleon Structure

Let us suppose that a free nucleon (at the origin) consists of three light (u and d) quarks under a (Lorentz scalar) confinement potential, V_c . Then, the Dirac equation for the quark field ψ_q is given by

$$[i\gamma \cdot \partial - m_q - V_c(r)]\psi_q(r) = 0, \quad (1)$$

where m_q is the bare quark mass.

Next we consider how Equation (1) is modified when the nucleon is bound in static, uniformly distributed (iso-symmetric) nuclear matter. In the QMC model [8] it is assumed that each quark feels scalar, V_s^q , and vector, V_v^q , potentials, which are generated by the surrounding nucleons, as well as the confinement potential. This assumption seems appropriate when the nuclear density ρ_B is near around normal nuclear matter density ($\rho_0 = 0.15 \text{ fm}^{-3}$). If we use the mean-field approximation (MFA) for the meson fields, Equation (1) may be rewritten as

$$[i\gamma \cdot \partial - (m_q - V_s^q) - V_c(r) - \gamma_0 V_v^q]\psi_q(r) = 0. \quad (2)$$

The potentials generated by the medium are constants because the matter distributes uniformly. As the nucleon is static, the time-derivative operator in the Dirac equation can be replaced by the quark energy, $-i\epsilon_q$. By analogy with the procedure applied to the nucleon in QHD [10], if we introduce the effective quark mass by $m_q^* = m_q - V_s^q$, the Dirac equation (2) can be rewritten in the same form as that in free space with the mass m_q^* and the energy $\epsilon_q - V_v^q$, instead of m_q and ϵ_q . In other words, the vector interaction has *no effect on the nucleon structure* except for an overall phase in the quark wave function, which gives a shift in the nucleon energy. This fact *does not* depend on how to choose the confinement potential, V_c . Then, the nucleon energy at rest in the medium is given by $E_N = M_N^*(V_s^q) + 3V_v^q$, where the effective nucleon mass M_N^* depends on *only the scalar potential*.

We can extend this idea to finite nuclei [8]. Let us suppose that the scalar and vector potentials in Equation (2) are mediated by the σ and ω mesons, and introduce their mean-field values, which now depend on position \vec{r} , by $V_s^q(\vec{r}) = g_\sigma^q \sigma(\vec{r})$ and $V_v^q(\vec{r}) = g_\omega^q \omega(\vec{r})$, respectively, where g_σ^q (g_ω^q) is the coupling constant of the quark- σ (ω) meson. Furthermore, we shall add the isovector vector meson, ρ , and the Coulomb field, A , to describe finite nuclei realistically. Then, the effective Lagrangian density for finite nuclei would be given by [8]

$$\begin{aligned} \mathcal{L}_{QMC} = & \bar{\psi}[i\gamma \cdot \partial - M_N^* - g_\omega \omega \gamma_0 - g_\rho \frac{\tau_3^N}{2} b \gamma_0 - \frac{e}{2}(1 + \tau_3^N) A \gamma_0] \psi \\ & - \frac{1}{2}[(\nabla \sigma)^2 + m_\sigma^2 \sigma^2] + \frac{1}{2}[(\nabla \omega)^2 + m_\omega^2 \omega^2] + \frac{1}{2}[(\nabla b)^2 + m_\rho^2 b^2] + \frac{1}{2}(\nabla A)^2, \end{aligned} \quad (3)$$

where ψ and b are respectively the nucleon and the ρ fields. m_σ , m_ω and m_ρ are respectively the masses of the σ , ω and ρ mesons. g_ω and g_ρ are respectively the ω -N and ρ -N coupling constants, which are given by $g_\omega = 3g_\omega^q$ and $g_\rho = g_\rho^q$ (where g_ρ^q is the quark- ρ coupling constant).

If we define the field-dependent σ -N coupling constant, $g_\sigma(\sigma)$, by [8]

$$M_N^*(\sigma(\vec{r})) \equiv M_N - g_\sigma(\sigma(\vec{r}))\sigma(\vec{r}), \quad (4)$$

where M_N is the free nucleon mass, it is easy to compare with QHD [10]. The difference between QMC and QHD lies only in the coupling constant g_σ , which depends on the scalar field in QMC while it is constant in QHD. However, this difference leads to a lot of favorable results [8].

Now we need a model for the structure of the nucleon involved to perform actual calculations. We here use the MIT bag model. In the present model, the bag constant, B , and the z parameter for the nucleon are fixed to reproduce the free nucleon mass ($M_N = 939$ MeV) and the free bag radius $R_N = 0.8$ fm. In the following we choose $m_q = 5$ MeV and set $m_\sigma = 550$ MeV, $m_\omega = 783$ MeV and $m_\rho = 770$ MeV. (Variations of the quark mass and R_N only lead to numerically small changes in the calculated results [8].) We then find that $B^{1/4} = 170.0$ MeV and $z = 3.295$.

For infinite nuclear matter, from the Lagrangian density (3), we can easily find the total energy per nucleon, E_{tot}/A , and the mean-field values of ω and ρ (which are respectively given by baryon number conservation and the difference in proton and neutron densities). The scalar mean-field is given by a self-consistency condition, $\partial E_{tot}/\partial \sigma = 0$ [8]. The coupling constants, g_σ^2 and g_ω^2 , are fixed to fit the average binding energy (-15.7 MeV) at ρ_0 for nuclear matter. Furthermore, the ρ -N coupling constant is used to reproduce the bulk symmetry energy, 35 MeV. We then find [8]: $g_\sigma^2/4\pi = 5.40$, $g_\omega^2/4\pi = 5.31$, $g_\rho^2/4\pi = 6.93$, and the nuclear incompressibility, $K \simeq 280$ MeV. Note that the model gives the variation of the nucleon bag radius, $\delta R_N^*/R_N = -0.02$, the lowest quark eigenvalue, $\delta x_q^*/x_q = -0.16$ and the root-mean-square radius of the quark wave function, $\delta r_q^*/r_q = +0.02$, at saturation density.

Using these parameters, we can solve a finite nuclear system. As an example, we show charge density distribution of ^{40}Ca in Figure 1. The QMC model can reproduce the properties of not only nuclear matter but also finite nuclei (for more details, see [8]).

Nucleon Mass in Nuclear Matter

Here we consider the nucleon mass in matter furthermore. The nucleon mass is a function of the scalar field. Because the scalar field is small at low density the mass may be expanded in terms of σ as

$$M_N^* = M_N + \left(\frac{\partial M_N^*}{\partial \sigma} \right)_{\sigma=0} \sigma + \frac{1}{2} \left(\frac{\partial^2 M_N^*}{\partial \sigma^2} \right)_{\sigma=0} \sigma^2 + \mathcal{O}(\sigma^3). \quad (5)$$

Since the interaction Hamiltonian between the nucleon and the σ field at the quark level is given by $H_{int} = -3g_\sigma^q \int d\vec{r} \bar{\psi}_q \sigma \psi_q$, the derivative of M_N^* with respect to σ is $-3g_\sigma^q \int d\vec{r} \bar{\psi}_q \psi_q \equiv -3g_\sigma^q S_N(\sigma)$, where we have defined the quark scalar charge in the nucleon, $S_N(\sigma)$, which is itself a function of σ . Because of a negative value of the derivative, the nucleon mass decreases in matter at low density.

Furthermore, we define the scalar-charge ratio, $S_N(\sigma)/S_N(0)$, to be $C_N(\sigma)$ and the σ -N coupling constant in free space to be g_σ (i.e., $g_\sigma = g_\sigma(\sigma = 0) = 3g_\sigma^q S_N(0)$). Using these quantities, we find

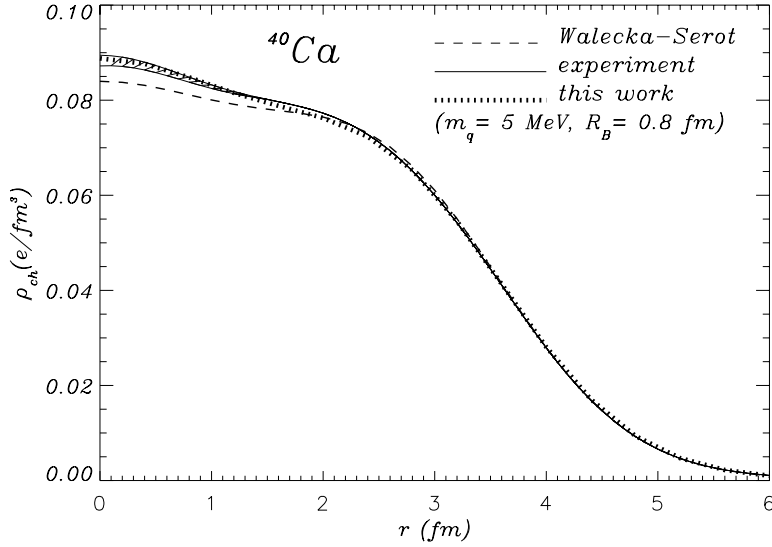


FIGURE 1. Charge density distribution for ^{40}Ca [8] compared with the experimental data and that of QHD.

TABLE 1. Inputs, parameters and some of the quantities calculated in the present study. The quantities with a star, *, are those quantities calculated at ρ_0 . We take $m_u = 5$ MeV.

	M_j (MeV)	R_j (fm)	$B^{1/4}$ (MeV)	z	M_j^* (MeV)	R_j^* (fm)
p (CSB)	937.6423 (input)	0.8 (input)	169.81	3.305	751.928	0.7950
n (CSB)	939.6956 (input)	0.8000	169.81	3.305	753.597	0.7951
N (SU(2))	939.0 (input)	0.8 (input)	169.97	3.295	754.542	0.7864

$$M_N^* = M_N - g_\sigma \sigma - \frac{1}{2} g_\sigma C'_N(0) \sigma^2 + \mathcal{O}(\sigma^3). \quad (6)$$

In general, C_N is a decreasing function because the quark in matter becomes more relativistic than in free space. Thus, $C'_N(0)$ takes a negative value. If the nucleon were structureless C_N would not depend on σ . Therefore, only the first two terms in the RHS of Equation (6) remain, which is exactly the same as the effective nucleon mass in QHD [10].

CHARGE SYMMETRY BREAKING IN QMC

Now we introduce the charge symmetry breaking in the QMC model [7,11]. The charge symmetry is explicitly broken at the quark level through their masses. We use different values for the u and d current quark masses, and the effective proton, M_p^* , and neutron, M_n^* , masses. At position \vec{r} in a nucleus (the coordinate origin is taken at the center of the nucleus), the Dirac equations for the quarks in the proton or neutron bag are given by

$$\left[i\gamma \cdot \partial_x - \left(\begin{pmatrix} m_u \\ m_d \end{pmatrix} - V_\sigma^q(\vec{r}) \right) - \gamma^0 \left(V_\omega^q(\vec{r}) \pm \frac{1}{2} V_\rho^q(\vec{r}) \right) \right] \begin{pmatrix} \psi_u(x) \\ \psi_d(x) \end{pmatrix} = 0, \quad (7)$$

where $|\vec{x} - \vec{r}| \leq R_j^*$ (j specifies proton or neutron). Note that we have assumed that the scalar potential is common to both the u and d quarks. The nucleon and meson fields are calculated self-consistently by solving a set of coupled non-linear differential equations, derived from the effective Lagrangian density (3) with the proper modifications caused by the different proton and neutron (or u and d quark) masses in MFA. Thus, the present calculation is free from the sort of double counting questioned by Auerbach [12], and includes the shell effects, which were discussed by Cohen et al. [13].

Before discussing the results obtained, we again need to specify the parameters and inputs used in the calculation [11]. They are summarized in Table 1. The bag constant, B , and the z parameter are determined by the bare proton mass, after allowing for the electromagnetic self-energy correction +0.63 MeV, with the bag radius, $R_p = 0.8$ fm, in free space. For the neutron, the procedure is the same as that for the proton, allowing for the electromagnetic self-energy correction, -0.13 MeV, but using the values of B and z determined

above and calculating the d current quark mass and the bag radius for the neutron. Thus, the u current quark mass ($m_u = 5$ MeV) is the basic input parameter used to fix the model parameters so as to reproduce the bare proton and neutron masses in free space. We found $m_d = 9.2424$ MeV in the present calculation.

The coupling constants, g_σ^q and g_ω^q , are determined so as to fit the saturation properties of symmetric nuclear matter [11]. In Table 1, SU(2) stands for the parameters and inputs obtained and used for the calculation when SU(2) symmetry is assumed, namely $m_u = m_d = 5$ MeV. We then found: $(g_\sigma^q, g_\omega^q) = (5.698, 2.744)$ for CSB, and $(5.685, 2.721)$ for SU(2). For the quark- ρ meson coupling constant, to make a realistic estimate, we here use the phenomenological value, $g_\rho^q = 4.595$, the value at zero three-momentum transfer corresponding to Hartree approximation, from Table 4.1 of Ref. [14]. (Note that because the QMC model does not contain the ρ -nucleon tensor coupling [8], this gives an unrealistically large value for the coupling constant [11].)

Proton and Neutron Masses in Nuclear Matter

As in Equation (5), the proton and neutron masses are again given by functions of σ in matter, and may be expanded in terms of σ at low ρ_B

$$M_p^* = M_p + (3g_\sigma^q)\frac{1}{3}[2S_{u/p}(0) + S_{d/p}(0)]\sigma + \mathcal{O}(\sigma^2), \quad (8)$$

$$M_n^* = M_n + (3g_\sigma^q)\frac{1}{3}[S_{u/n}(0) + 2S_{d/n}(0)]\sigma + \mathcal{O}(\sigma^2). \quad (9)$$

Because $m_u \neq m_d$, the u-quark scalar charge is no longer the same as the d-quark scalar charge. We have therefore introduced four kinds of quark scalar charges in the expansion: $S_{i/j}(\sigma) = \int_{V_j} d\vec{r} \bar{\psi}_{i/j} \psi_{i/j}$, where i denotes u or d quark, V_j is the volume of j ($= p$ or n) and $\psi_{i/j}$ is the i quark wave function in j . Since the proton consists of two u quarks and one d quark, the derivative of M_p^* with respect to σ is given by $2S_{u/p} + S_{d/p}$. Similarly, the derivative for the neutron is given by $S_{u/n} + 2S_{d/n}$.

Taking the difference between the in-medium neutron and proton masses, we find

$$\Delta_{np}^* \equiv M_n^* - M_p^* = \Delta_{np} - (3g_\sigma^q)[S_n(0) - S_p(0)]\sigma + \mathcal{O}(\sigma^2), \quad (10)$$

where $\Delta_{np} = M_n - M_p$, $S_n(0) = \frac{1}{3}[S_{u/n}(0) + 2S_{d/n}(0)]$ and $S_p(0) = \frac{1}{3}[2S_{u/p}(0) + S_{d/p}(0)]$. Here we may expect that $S_{u/j} < S_{d/j}$ because the u quark is *more relativistic* than the d quark in nuclear matter ($m_u < m_d$) — note that the quark scalar charge is given in terms of $\bar{\psi}_q \psi_q$ in matter. Thus, we find that $S_n(0) > S_p(0)$ and then $\Delta_{np}^* < \Delta_{np}$ in nuclear medium.

In Figure 2 we show the neutron-proton effective mass difference calculated in symmetric nuclear matter, including the electromagnetic self-energy

corrections. One notices that the mass difference becomes smaller as the density increases. This behavior works in the right direction to resolve the ONS anomaly.

The ONS Anomaly in Mirror Nuclei

Now we are in a position to show our results of the ONS anomaly in mirror nuclei [11]. We first present the calculated single-particle energies for ^{17}F and ^{17}O in Table 2. These mirror nuclei have a common core nucleus, ^{16}O , and have an extra valence proton for ^{17}F and neutron for ^{17}O . In order to focus on the strong interaction effect for the valence proton and neutron, the Dirac equations are solved without the Coulomb and ρ -meson potentials, or the electromagnetic self-energy corrections, and keeping only the charge symmetric σ and ω mean field potentials. Consistently, the valence nucleon contributions are not included in the Coulomb and ρ -mean field source densities in the core nucleus. However, for the nucleons in the core nucleus, electromagnetic self-energy corrections and the Coulomb potential as well as the ρ mean field potential are included in addition to the σ and ω mean field potentials in

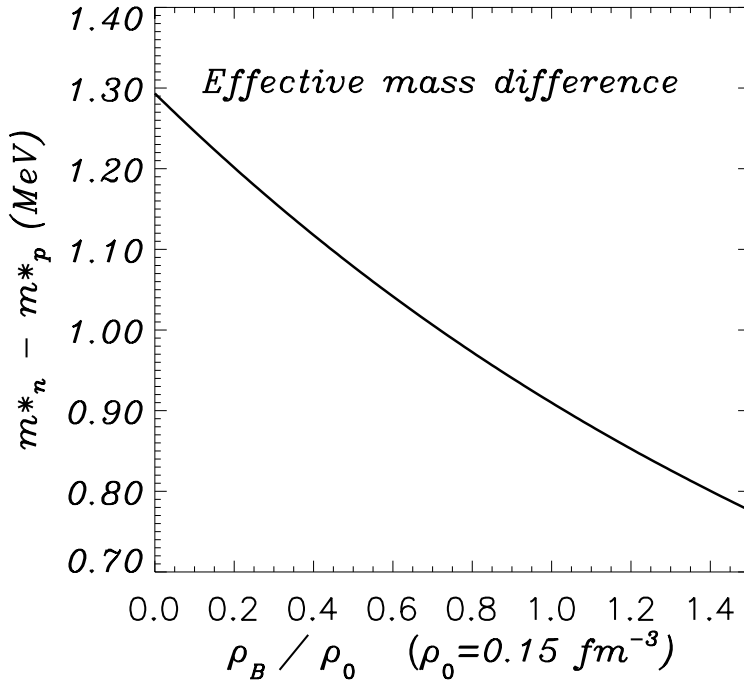


FIGURE 2. Neutron-proton effective mass difference in symmetric nuclear matter with the electromagnetic self-energy corrections.

TABLE 2. Calculated single-particle energies (in MeV) for ^{17}F and ^{17}O .

	CSB		SU(2)	
	^{17}F	^{17}O	^{17}F	^{17}O
p $1s_{1/2}$	-28.800	-28.805	-28.663	-28.663
1p $_{3/2}$	-14.154	-14.158	-14.032	-14.032
1p $_{1/2}$	-12.495	-12.499	-12.383	-12.383
n $1s_{1/2}$	-33.367	-33.372	-32.967	-32.967
1p $_{3/2}$	-18.259	-18.263	-17.918	-17.918
1p $_{1/2}$	-16.587	-16.590	-16.258	-16.258
valence	p	n	p	n
1d $_{5/2}$	-3.918	-4.099	-3.848	-3.848

solving the Dirac equations. Results are shown for two cases in Table 2: calculation with charge symmetry breaking (denoted by CSB) and calculation performed assuming SU(2) symmetry (denoted by SU(2)).

The SU(2) results for ^{17}F and ^{17}O agree perfectly with each other as they should. Single-particle energies in the cores of ^{17}F and ^{17}O are slightly different for CSB. This difference is induced by the different (effective) masses for the valence proton and neutron, arising from the charge and density dependence of their coupling to the self-consistent scalar mean field. This also causes a second order effect on the Coulomb and ρ -meson potentials through the self-consistency procedure.

It is interesting to compare the binding energy differences between the valence proton in ^{17}F and neutron in ^{17}O . In CSB, the result gives, $E(p)(1d_{5/2}) - E(n)(1d_{5/2}) \simeq 0.18$ MeV, while the SU(2) case is zero as it should be. This amount already shows a magnitude similar to that of the observed binding energy differences.

In Table 3, we summarize the calculated single-particle energies for the valence proton and neutron of several mirror nuclei (in CSB) [11]. Comparing the ρ -potential contributions for the hole states with core plus valence states, one notices the shell effects due to the ρ -potentials. These results reflect the difference in the shell structure, namely the hole states tend to have larger ρ -potential contributions than the core plus valence nucleon states.

The binding energy differences obtained indicate that the prime CSB effects originate in the u-d current quark mass difference. The calculated binding energy differences give of the order of about a few hundred keV. This is precisely the order of magnitude which is observed as the ONS anomaly [3,5].

SUMMARY

Using the QMC model, we have discussed CSB in nuclear medium and calculated the ONS anomaly in mirror nuclei, including the quark degrees

TABLE 3. Calculated single-particle energies of mirror nuclei. For each nucleus, the top row shows the single-particle energy of the valence proton or neutron (the orbit is also indicated). δE_ρ stands for the contribution from the ρ -meson central and spin-orbit potentials of the core nucleus. The discrepancies between the experimental values and the theoretical expectations in the absence of charge symmetry violating strong interactions are taken from Table II of Ref. [5], by averaging over the theoretical values.

	$^{15}\text{O(p)}$	$^{15}\text{N(n)}$	$^{17}\text{F(p)}$	$^{17}\text{O(n)}$
$1p_{1/2}$ or $1d_{5/2}(\text{MeV})$	-14.397	-14.631	-3.918	-4.099
$\delta E_\rho(\text{MeV})$	-0.055	0.056	-0.005	0.005
Total(MeV)	-14.452	-14.575	-3.923	-4.094
$\delta E = E(p) - E(n)$	$\delta E =$	123(keV)	$\delta E =$	171(keV)
	observed =	230(keV)	observed =	220(keV)
	$^{39}\text{Ca(p)}$	$^{39}\text{K(n)}$	$^{41}\text{Sc(p)}$	$^{41}\text{Ca(n)}$
$1d_{3/2}$ or $1f_{7/2}(\text{MeV})$	-16.407	-16.689	-6.970	-7.210
$\delta E_\rho(\text{MeV})$	-0.087	0.088	-0.006	0.006
Total(MeV)	-16.494	-16.601	-6.976	-7.204
$\delta E = E(p) - E(n)$	$\delta E =$	108(keV)	$\delta E =$	228(keV)
	observed =	340(keV)	observed =	460(keV)

of freedom explicitly. We stress that the present contribution to the ONS anomaly is based on a very simple but novel idea, namely the slight difference between the quark scalar densities of the u and d quarks in a bound nucleon, which stems from the u and d quark mass difference [7,11]. This implies that the in-medium proton- σ and neutron- σ coupling constants differ from their values in free space and that the neutron-proton effective mass difference is reduced in matter.

Our results were obtained within an explicit shell model calculation, based on quark degrees of freedom. They show that once CSB is set through the u and d current quark mass difference so as to reproduce the proton and neutron masses in free space, it can produce binding energy differences for the valence (excess) proton and neutron of mirror nuclei of a few hundred keV. The origin of this effect is so simple that it is natural to conclude that a sizable fraction of CSB in mirror nuclei arises from the density dependence of the u and d quark scalar densities in a bound nucleon.

It is a fascinating challenge for the future to compare this result with the traditional mechanism involving $\rho - \omega$ mixing [4]. This will involve the issue of the possible momentum dependence of the $\rho - \omega$ mixing amplitude [3,15]. In addition, one would need to examine whether there is any deeper connection between these apparently quite different sources of charge symmetry violation.

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